DESIGN OF AN AMBIENT AEROSOL SAMPLING SYSTEM FOR HIGH AND MEDIUM SPEED APPLICATIONS

A Thesis

by

HAMMAD IRSHAD

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2002

Major Subject: Mechanical Engineering

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ABSTRACT

Design of an Ambient Aerosol Sampling System

for High and Medium Speed Applications. (December 2002)

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Two ambient sampling systems were designed and tested for high speed sampling application for a wind speed range of 4.47 m/s to 26.82 m/s. These systems will be used as inlets for sampling of bioaerosol from air. These systems consist of shrouded probes for sampling at higher speeds and omni-directional inlets for low speed ambient sampling. The two systems operate at 780 L/min and 90 L/min. Another system was designed and tested for medium speed ambient sampling. This unit will be used as a reference sampler for speed ranges from zero to 20.12 m/s. This system consists of a Sierra-Andersen SA-246 inlet for sampling at speeds up-to 6.71 m/s (15 mph) and a shrouded probe operating at variable flow rate for sampling in speed range of 6.71 m/s and 20.12 m/s. An aircraft-borne shrouded probe was also tested at wind speeds as high as 50 m/s in an upgraded high speed wind tunnel.

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INTRODUCTION

General

The threat of the use of chemical and biological weapons exists across the spectrum of military operations. Despite the dissolution of the Warsaw Pact, the downfall of communism in the former USSR, and extensive efforts to negotiate treaties, which would eliminate biological weapons from military arsenals, the number of countries pursuing an offensive biological warfare program continues to increase. As many as thirteen countries are developing, or are suspected of developing, biological weapons. The threat biological agents include microorganisms and toxins. These biological agents can be delivered to target areas virtually anywhere in a theater of operation by surface-to-surface missiles, aircraft bombs, multiple rocket launchers, artillery, and/or special forces operating in rear areas. Spray devices and aerosol generators are available for disseminating some biological agents. While primarily an inhalation hazard, there is evidence that a number of countries may be developing biological agents, which are percutaneous hazards.

Production of biological warfare materials does not require specialized equipment or advanced technology. Biological agents are far more potent than chemical warfare agents, i.e., small amounts of these materials can produce large numbers of casualties. It is increasingly likely that the U.S. will encounter the use of biological weapons at the operational and tactical levels in a regional conflict.

This thesis follows style and format of *Aerosol Science and Technology*.

Current national military strategy specifies a worldwide force protection capability that requires detection, identification, and vaccination in order to protect the U.S. forces. This capability will provide commanders with an effective system to detect and presumptively identify biological warfare (BW) agents. Its primary purpose is to limit the effects of biological agent attacks, which have the potential for catastrophic effects to U.S. forces at the operational level of war. It may also assist medical personnel in determining effective preventative measures, prophylaxis, and the appropriate treatment if exposure occurs. Detection and identification of biological agents within the theater of operations will increase the effectiveness of U.S. forces by limiting adverse impacts on operations and logistical systems.

Aerosol Sampling

Aerosol sampling from ambient air with aerosol transported to a filter or analyzer is an integral part of many aerosol studies. If correct results are to be obtained, the difference in concentration and particle size distribution between the original aerosol and the sampler must be as small as possible. Difference may result from deposition of the aerosol in the transport system through which the aerosol is passed, as well as biases present at the inlet to the sampler (Fuchs, 1964).

To provide meaningful data, the inlet must allow all particles of interest to be collected with the same efficiency independent of sampling conditions. These conditions include mean velocity (magnitude and three-dimensional direction), turbulence scale and intensity, and extraneous airborne matter (rain, snow, insects, debris, etc.) (Wedding, 1980).

The sampling of aerosols can be broadly classified in two main categories, a) ambient sampling, i.e., sampling in the free atmosphere, and b) source sampling of aerosols in ducts, stacks, pipes, and moving fluid streams. This study deals with sampling of ambient bioaerosols.

There are biological, in addition to physical, considerations inherent to bioaerosol sampling. For example, biological sampling may require aseptic handling to prevent contamination and special attention to the viability of the organisms during the process of sampling and analysis (Hinds, 1999). We will concentrate on the physical aspect of bioaerosol sampling without discussing the biological aspect in detail.

Ambient sampling can be further classified according to the particular application into the following three classes:

1. Sampling in open atmosphere with stationary sampling equipment. Wind velocity can vary from still air to up to 6.7 m/s (24 km/hr). The direction of wind and turbulence intensity can also vary in these applications.
2. Sampling in workspace areas with fixed sampling equipment. Very low wind velocities (typically zero to 0.5 m/s) are encountered in such applications.
3. Atmospheric sampling with the device mounted on a moving object e.g. a navy aircraft carrier, an army vehicle, or an aircraft.

Parameters Used as Indicators of Aerosol Sampling

As mentioned earlier, the first component in any sampling system is an aerosol sampling inlet whose performance is indicated by its ability to transmit aerosol and is quantified by its transmission ratio (T), which is defined as:

$$T = \frac{\text{Particle concentration at exit plane of a probe}}{\text{Particle concentration in the free stream}} \qquad [1]$$

From the above relation it is easy to see that a probe with a transmission ratio of unity will result in a particle concentration at the exit plane of the probe, equal to that in the free-stream. In other words, the aerosol sample at the exit of the probe will be representative of the free-stream. For continuous monitoring of aerosol it is usually desirable to obtain a representative sample of free-stream, on a real-time basis. This implies that ideally a transmission ratio of unity is required for any sampling probe used for that purpose. It is also desirable that the transmission ratio should remain near unity over variations of operating conditions that may occur during actual sampling situations.

The transmission ratio is the net result of two effects, particle aspiration to the inlet plane of the sampling probe and particle deposition on the inner wall of the probe. The first effect is quantified as the aspiration ratio (A) and the second by the wall loss ratio (Wl). These are defined as:

$$A = \frac{\text{Particle concentration at probe inlet plane}}{\text{Particle concentration in the free stream}} \qquad [2]$$

$$Wl = \frac{\text{Particle concentration deposited on inner wall of probe}}{\text{Particle concentration at probe inlet plane}} \qquad [3]$$

From Equations (1), (2), and (3) it can be further concluded that

$$T = A*(1-Wl) \qquad [4]$$

Equation (4) gives the relationship among the transmission ratio, the aspiration ratio and the wall loss ratio. It emphasizes that variation of the transmission ratio with different flow parameters and particle characteristics is governed by variation of the aspiration ratio and the wall loss ratio with these parameters.

Ambient Sampling

Until 1972, characterization of atmospheric particulate matter was accomplished through the use of the standard high volume ("Hi-Vol") samplers, which measure total suspended particulate (TSP) and draw in air at a flow rate of 1.41 m^3/min (50 cfm). This approach did not supply acceptable information for a variety of reasons. Initially, the collection capability of samplers was found to be a strong function of particle size, wind speed, and sampler orientation. Characterization of the aerosol concentration is rendered speculative when the upper size limit is variable. Hi-Vol samplers are not size-segregated near the center of the bimodal mass distribution (Wedding, 1982). These shortcomings prompted the Environmental Protection Agency (EPA) to examine conventional impactors as a means of fractionating the sample prior to collection. Initially, it was recommended that it should take the form of a selection curve that exhibits a 50% cut point at 15 μm AD, which was subsequently changed to 10 μm AD. Cut point (D_{50}) is the aerodynamic diameter for which the inlet shows 50% collection efficiency.

particles, PM-2.5. These standards are designed to control particles smaller than 2.5 μm in aerodynamic diameter. These fine particles pose a significant risk to human health because of their ability to penetrate and deposit in the tracheal, bronchial, and alveolar regions of the respiratory duct.

Source Sampling

The simplest aerosol sampler used for fast-moving aerosol particles is a thin-walled probe, aligned with the flow, facing the wind. Sampling is isokinetic when the inlet axis of the sampler is aligned parallel to the gas streamlines and the gas velocity entering the probe equals the free-stream velocity approaching the inlet. Anisokinetic sampling is a failure to sample isokinetically and may result in a distortion of size distribution and a biased estimate of the concentration (Hinds, 1999). If sampling is isokinetic, the aspiration will be unity, regardless of particle size and inertia. However, isokinetic sampling does not ensure that there are no losses between the inlet and the collector or analyzer. Instead, it guarantees only that the concentration and size distribution of the aerosol entering the tube is the same as that in the flowing stream. Even with efficient entry of particles into a sampler inlet, particles may be lost in the sampling inlet. These losses can be very significant in small-sized inlets that are required when isokinetically sampling high speed flows at small sampling flow rates. McFarland and Rodgers (1993) proposed alternate reference methodology (ARM) for a continuous monitoring system as a means of obtaining a more representative sample. The U.S. Environmental Protection Agency has accepted the use of ARM for all U.S. Department of Energy (DOE) nuclear facilities. The main component of ARM is the use of shrouded sampling probes at well-mixed locations. The concept of the shrouded probe was developed to reduce these losses. It was found that, unlike isokinetic probes, where the transmission of aerosol in probe varies significantly with change in velocity of the moving stream, flow angle, and the particle size, transmission remains almost constant in a shrouded probe. The principle of operation of a shrouded probe is presented in several studies (McFarland et al., 1989; Chandra, 1992; Gong et al., 1993; Chandra and McFarland, 1995) and is briefly discussed in the following paragraph.

In this type of device ,Figure 1, a shroud is placed around the sampling probe. As the free-stream enters the shroud, it decelerates due to blockage in the form of reduced flow area at the probe waistline. Varying the probe waistline diameter can control this blockage, and therefore the reduction in velocity. This blockage reduces the free-stream velocity to a value inside the shroud that is typically 25 to 40% of the free-stream velocity. In order to adjust this reduction in velocity, the streamlines have to bend outward when entering the shroud. A numerical study by Gong et al. (1993) and streakline analysis by McFarland et al. (1989) demonstrated that the streamlines on the outer region bend significantly more than those in the core region. There is an inertial enrichment of aerosol in the shroud, but it is concentrated towards the outer edges of the shroud and the flow that passes through that region is discharged through the probe waistline region. On the other hand, the core region, which is sampled by the inner probe, is relatively unbiased with respect to concentration and is at low velocity compared with free-stream. The low sampling velocity ensures low wall loss and less sensitivity to variation in free-stream conditions.

Objective

The Aerosol Technology Laboratory at Texas A&M University is developing systems for ambient sampling of biological aerosol at wind speeds up to 26.82 m/s (60 miles per hour). This study deals with the design and experimental testing of inlets for this system. Following is a detailed explanation of objectives of this study:

(a) The first objective of this study was to develop inlet systems for sampling of bioaerosols in the atmosphere at high wind speeds. These systems are required for installation on JPBDS (Joint Point Biological Detection System) samplers placed on U.S. Navy aircraft carrier ships. The normal cruising speed of a carrier ship is in the range of 15.6 m/s (35 mph). Considering that the velocity of air can be as high as 11.2 m/s (25 mph), the goal is to develop a sampling system that can be operated over a range of speeds from zero to 26.82 m/s (60 miles/hr). These systems should be able to operate continuously and handle the water entering the systems during unfavorable weather conditions at the sea. Also they should be able to remove any insects, large-sized debris, etc. present in the sampled air stream.

Two inlets are required for the JPBDS application.

1. Trigger inlet with a flow rate of 90 L/min.
2. Sampler inlet with a flow rate of 780 L/min.

The trigger system operates continuously and checks samples for attributes indicative of BW agents. In case of any indication of BW agents in the sampled air stream, the main sampler inlet starts operating to collect the bioaerosol and the sample is transported to a system that concentrates the particles in the 780

L/min sampled air to a liquid stream that flows at a rate of about 1 mL/min. The resultant hydrosol is then used for analysis and identification of the bioaerosols in the atmosphere.

The quantifiable goals of the present study are:

1) Design an aerosol extraction system that can sample with a transmission ratio of at least 80% for 10 μm AD aerosol particles over a range of wind speeds from 0.5 to 27 m/s.

2) Transmission ratio for the system should be at least 50% for a particle size of 13 μm AD.

$$T = C_e / C_\infty$$

Where: T = aerosol transmission; C_e = aerosol concentration at the exit plane of the inlet; and, C_∞ = aerosol concentration in the free wind stream.

3) The system should be able to give consistent readings for a change in the yaw angles to 45 degrees. The variation in the penetration for 10 μm particles for the given yaw angle range should not be more than 10%.

The objective is to characterize the collection efficiency of the sampling system. The result should be in the form of collection efficiency as a function of aerodynamic particle diameter and wind speed. Also, collection efficiency of the shrouded probes will be characterized for a given particle size and wind speed as a function of yaw angle, for both the trigger shrouded probe and the sampler shrouded probe.

(b) The second objective is to design a sampling system for medium speed applications, capable of sampling continuously, over a range of wind speeds from still air to 45 mph.

The system should satisfy the following requirements:

1) It should be able to sample with 50% collection efficiency for 10 μm AD particles for wind speed ranges from still air to 15 mph. The slope of the collection curve should be 1.5. Sampling flow rate is fixed at 16.7 L/min for this speed range.

2) System should be capable of sampling with transmission efficiency of more than 90% for particle sizes from 5 μm to 15 μm AD, for wind speed ranges from 15 mph to 45 mph. Maximum sampling flow rate is limited to 50 L/min.

The objective is to characterize the collection efficiency of the sampling system. The result should be in the form of collection efficiency as a function of aerodynamic particle diameter and wind speed.

This system will be used as a reference sampler for testing different aerosol devices. Due to this requirement, the transmission ratio of this system in two wind speeds i.e., from still air to 15 mph, and from 15 mph to 45 mph, should be well defined.

(c) Testing of the aircraft-borne shrouded probe that is to be used in a program for sampling marine aerosols for mercury. Because some of the mercury will be either in, or on salt aerosol particles that have sizes on the order of 10 μm AD, assurance is needed that aerosols can be efficiently sampled by the shrouded probe. Also, it is required that the particles can be transported with minimal losses from the inlet to the collectors and analyzers in the aircraft.

The objective is to characterize the collection efficiency and optimize the system for maximum transmission ratio of the shrouded probe and the sampling system. The result should be in the form of collection efficiency as a function of wind speed for 10 μm AD particles.

TEST APPARATUS AND PROCEDURES

General

Tests can be conducted with monodisperse liquid aerosols to characterize the penetration of particles through an aerosol-sampling inlet. A liquid monodisperse aerosol is generated with a Berglund-Lui (Berglund and Lui, 1973) vibrating orifice aerosol generator (TSI, Inc., St. Paul, MN), Figure 2. Typically, the aerosol is formed from atomization of a non-volatile liquid such as oleic acid to which is added a fluorescent analytical tracer (e.g., sodium fluorescein). The size of the aerosol droplets is determined by impacting them on a glass slide coated with an oil-phobic film. The droplets are then measured with an optical microscope. From knowledge of the degree of gravitational flattening of the oil droplets on the slide, the original spherical size of the droplets is calculated (Olan-Figueroa et al., 1982). An Aerodynamic Particle Sizer (APS Model 3300, TSI, Inc., St. Paul, MN) is used to monitor the size distribution of the aerosol and concentration as a quality assurance procedure. However, because of the errors introduced by this apparatus in sizing the liquid particles (Baron, 1986), it was not used for actual size measurement. The aerosol thus generated is drawn either into a wind tunnel or a mixing duct depending upon the type of test and equipment being tested.

A 0.86 m (34 inch) diameter wind tunnel was used for testing of the shrouded probes for wind speeds up to 13.41 m/s (30 mph). A schematic diagram and a picture of the wind tunnel are shown in Figure 3. Speeds higher than 13.41 m/s (30 mph) could not be achieved with the tunnel configuration shown in Figure 3 due to limitations of the fan/motor and the plenum chamber.

In order to test the inlets at speeds up to 44.7 m/s (100 mph), the wind tunnel was redesigned and upgraded. Upgrading included a new fan and motor with a new speed controller. The fan has a capacity of 4.72 m^3/s (10,000 cfm) at 3 kPa (12.0 inches water) static pressure (IAP, Inc., Phillips, WI). The motor is rated at 29.8 kW (40 hp), 3600 rpm (Marathon Electric). The variable frequency drive used with this motor is 29.8 kW (40 hp) at 460 volt (Model VLT 6000, Danfoss Graham, Milwaukee, WI). The new plenum chamber, which can withstand higher pressure, was designed and fabricated for wind speeds up to 44.7 m/s (100 mph). The test section was reduced from a 0.86 m (34 inch) circular cross section to a 0.36 m x 0.25 m (14"x 10") rectangular cross section through a 1.5 m (5 ft) long reducer. A 0.9 m (3 ft) long straight section followed the reducer to stabilize the flow conditions at the test section (Figure 4). Tests with SF_6 gas indicated that the concentration profile at the test section has a coefficient of variation (*COV*) of 22% at low speeds (~5.6 m/s). This high value of *COV* is not acceptable in the wind tunnel used for aerosol testing. In order to reduce the *COV* an industrial gas blender (AirBlender, Model ABG 34 C8F-AL, Blender Products, Denver, CO) was installed downstream of the plenum chamber to improve the mixing. The *COV* after the installation of AirBlender was found to be 8.2% at 5.6 m/s. The *COV* of concentration was less than 6% at higher speeds of 25.4 m/s and 45.7 m/s. Since the basic purpose of the smaller cross section was to test inlets at higher speeds, these results were in acceptable range. The procedures for the gas mixing study can be found in McFarland

(1996). The concentration profile of the wind tunnel test cross section was also checked with liquid aerosols. For polydisperse particles less than 3 μm the *COV* was found to be 2.51% at a wind speed of 5.44 m/s. For 10 μm AD particles, which is the reference size for most aerosol inlet studies, the *COV* was found to be 2.67% at a wind speed of 5.44 m/s.

Test Protocol

An inlet, under testing, is operated side-by-side with an unshrouded isokinetic probe (Figures 3 and 4). Both the inlet and the unshrouded isokinetic probe are operated for a fixed time. The flow rates through the inlets and isokinetic samplers are continuously monitored with digital mass flow meters (Model 820, Sierra Instruments, Monterey, CA) or calibrated rotameters.

At the wind tunnel outlet, aerosol is sampled with an isokinetic nozzle followed by a glass-fiber filter (P/N 61638, Gelman Sciences, MI). Particles penetrating through the inlet are also collected on a glass fiber filter.

The filters (both from the reference isokinetic probes and the inlet under test) are placed in solutions containing 50% isopropyl alcohol and 50% distilled water (v/v) to elute the fluorescent tracer. The inlet wall of the isokinetic nozzle is also rinsed with a solution containing 50% isopropyl alcohol and 50% distilled water (v/v) to recover any inadvertently deposited particulate matter.

The relevant concentrations of fluorescent tracer in the solutions are measured with a fluorometer (Model 450, Sequoia-Turner Corp., Mountain View, CA). Relative concentrations of the fluorescent tracer in the solutions were calculated using the following formula.

$$C = \frac{F * V}{t * Q} \qquad [5]$$

Where,

F= fluorometer numerical reading,

V= measured solution liquid volume,

t= testing time for each filter, and

Q= aerosol flow rate.

By dividing the relative concentration of the test filter solution by the relative concentration of the reference filter solution and wall wash solution, the percentage of particulate mass penetrating the inlet is determined. From this the transmission, aspiration and wall loss ratio of the inlet can be written as:

$$T = \frac{C_{f,tst}}{C_{f,iso} + C_{w,iso}} \qquad [6]$$

$$A = \frac{C_{f,tst} + C_{w,tst}}{C_{f,iso} + C_{w,iso}} \qquad [7]$$

$$WL = \frac{C_{w,tst}}{C_{f,tst} + C_{w,tst}} \qquad [8]$$

Where: C_f = aerosol concentration determined from analysis of the filters either from the test inlet or the isokinetic probe; and, C_w = aerosol concentration determined from analysis of the wall wash of the probe. The subscript *tst* and *iso* stand for the probe being tested and the isokinetic probe, respectively.

Velocity of the air stream at test section was monitored for all test conditions. A TSI VelociCal Meter (Model no. 8355, TSI Inc., St. Paul MN) was used for the measurement of velocity.

When characterizing the efficiency of a device that does not extract aerosol from a free-stream, aerosol is introduced into a mixing duct (Figure 5). At the other end of the mixing duct, the aerosol is drawn into the instrument being tested and collected on a glass-fiber filter placed downstream of the instrument. Aerosol concentration in the stream is determined by removing the instrument and operating only the glass-fiber filter at the same flow rate and for the same time duration. The later filter gives the reference aerosol concentration. The reference filter and the instrument being tested are run alternatively and analysis of the filters proceeds just as in the characterization of an extraction device.

Glass fiber filters (type A/D and type A/E, Gelman Sciences) were used for collecting the aerosol particles. The filter sizes used were standard 47-mm diameter and 8"x 10" rectangular filters depending on the particular requirement.

Design of Sampling System for High Speed Application

As mentioned earlier, the high speed application for the JPBDS requires two inlet systems that are designed to operate at different flow rates. One, designed for 90 L/min samples continuously and acts as a trigger for the main 780 L/min sampling probe. The purpose was to design inlets, which could achieve the quantifiable goals listed under Objectives in the first section. Also the inlets must remove insects, debris, and similar foreign material from the sampled air streams. Additionally, the inlet systems should be able to remove water spray that may be encountered during unfavorable weather conditions at sea.

These goals for high-speed sampling were met by designing and testing two shrouded probes as inlets for the system mentioned above. Figures 6 and 7 show the general configuration of the 780 L/min and 90 L/min shrouded probes used for this study respectively. Downstream from the shrouded probes, a conventional impactor (Figure 8) was installed to remove particles of size higher than that of interest. The conventional impactor was designed not only to remove the big particles from the sampled air stream, but also the water spray that could enter the shrouded probe during inclement weather conditions. Figure 9 shows the complete system used for trigger JPBDS sampling system. It consists of a shrouded probe and a BAWS (Biological Aerosol Warning System) inlet. Both the inlets are connected to a demister via ball valves. BAWS inlet will be used for sampling at low wind speeds up-to 4.47 m/s (10 mph) and for higher wind speeds shrouded probe will be used with inlet facing the wind direction. A wind direction sensor and controller, developed by the U.S. Army Edgewood Chemical Biological Center (ECBC), Edgewood, Maryland will be linked to the shrouded probes to keep them aligned with the prevailing wind direction. Figure 9 shows the complete setup of shrouded probes with a wind direction sensor, controller, and demisters. Following is the description of various tests performed for this study.

Testing of High Speed Application Shrouded Probes at Different Free-stream Velocities

The two shrouded probes (trigger and main sampling probe) were tested at different free-stream velocities. For wind speeds up to 13.41 m/s (30 mph) each probe was installed at the test section of the wind tunnel along with two isokinetic probes. Each probe was tested at 4.47, 8.94, and 13.41 m/s (approximately 10, 20, and 30 mph, respectively). Also in order to study the behavior of these probes at very low wind velocities they were tested at wind velocities of 0.5 m/s and 1 m/s. The particle size used for 90 L/min shrouded probe at low velocities was 10 μm AD and for 780 L/min shrouded probe it was 13 μm AD.

For speeds higher than 13.41 m/s (30 mph), the wind tunnel configuration was that with 0.36 m x 0.25 m (14" x 10") rectangular test section. Each probe was installed at the test location with one isokinetic probe and tested at 17.88, 22.35, and 26.82 m/s (40, 50, and 60 mph, respectively). The velocity of air at the test section was adjusted by controlling the speed of the electric motor/fan of the wind tunnel using the variable frequency drive.

The complete JPBDS trigger system (with shrouded probe and BAWS inlet installed on the demister through ball valves) was tested for 10 μm AD particles at 6.71, 13.41, and 26.82 m/s (15, 30, and 60 mph respectively) wind speeds with shrouded probe working as an inlet. Also it was tested for 10 μm AD particles at 3.6 m/s and 6.71 m/s (8 and 15 mph, respectively) using BAWS inlet as sampler. The system was also tested at 3.6 m/s (8 mph) for 5, 10, 15, and 20 μm AD particles.

Testing of High Speed Application Shrouded Probes at Different Yaw Angles

The effect of yaw angle on the transmission of aerosols through the 90 L/min shrouded probe was tested at 2.25 m/s (5 mph) for 10 μm AD particle size at four different angles. These were 0°, 22.5°, 45°, and 90° to the wind direction. Transmission ratio was plotted as a function of yaw angle for these values of yaw angle. Similarly, the 780 L/min shrouded probe was tested at 2.25 m/s (5 mph) for 10 μm AD particles for three different yaw angles, i.e. 0°, 22.5°, and 45°.

Testing of High Speed Application Shrouded Probes for Different Particle Sizes

The two shrouded probes were tested for four different particle sizes, i.e., 5, 10, 15, and 17.5 μm AD. Penetration/transmission of each of the probes for each of the particle size was experimentally determined at six different wind speeds from 4.47 m/s (10 mph) to 26.82 m/s (60 mph) with an interval of about 4.47 m/s.

Testing of Demister with Different Particle Sizes

The demister for the trigger shrouded probe was tested statically at 90 L/min flow rate using the system shown in Figure 5. The aerosol is drawn into the demister followed by a glass-fiber filter for a fixed time and a fixed flow rate. Aerosol concentration in the stream is determined by removing the instrument and operating only the glass-fiber filter at the same flow rate and for the same time duration. The latter filter gives the reference aerosol concentration.

Design of Sampling System for Medium Speed Application

The medium speed application system will be used as a reference sampler for different applications. Due to this requirement, the transmission ratio of this system in two wind speed ranges, i.e., from still air to 6.71 m/s (15 mph) and from 6.71 m/s (15 mph) to 20.12 m/s (45 mph) should be well defined. In order to cater for these two wind speed ranges, the use of two different inlets was proposed. For wind speeds from still air to up to 6.71 m/s (15 mph), a Sierra-Andersen atmospheric inlet SA-246, Figure 10, operating at 16.7 L/min will be used. SA-246 inlet has long been used in atmospheric sampling and its transmission curve (D_{50} at 10 μm, slope 1.45) is well defined. For higher speed range, i.e., from 6.71 m/s (15 mph) to 20.12 m/s (45 mph) a variable flow shrouded probe will be used. The flow rate through the shrouded probe at 6.71 m/s (15 mph) will be 16.7 L/min and it will increase proportionally to 50 L/min at 20.12 m/s (45 mph). Figures 10 and 11 show the general configuration of the SA-246 inlet and variable flow shrouded probe, respectively. Following is the description of various tests performed for this study.

Testing of Medium Speed Application Shrouded Probe at Different Free-stream Velocities

The shrouded probe was tested at different free-stream velocities. For wind speeds up to 13.41 m/s (30 mph) the probe was installed at the test section of the wind tunnel along with two isokinetic probes. The probe was tested at 6.71 m/s and 13.41 m/s (15 mph and 30 mph, respectively). For speeds higher than 13.41 m/s (30 mph), a 0.36 m x 0.25 m (14" x 10") rectangular test section was used. The air blender was used to improve the aerosol concentration profile at the test section. The probe was installed at the test section with one isokinetic probe and tested for 20.12 m/s (45 mph). The velocity of air at the test section was adjusted by controlling the speed of the electric motor/fan of the wind tunnel with a variable frequency drive.

Testing of Medium Speed Application Shrouded Probe for Different Particle Sizes

The shrouded probe was tested for three different particle sizes, i.e., 5, 10, and 15 μm AD. Transmission of the shrouded probe was experimentally determined at three different wind speeds 6.71, 13.41, and 20.12 m/s (15, 30, and 45 mph, respectively) for each particle size.

Testing of Aircraft-Borne Shrouded Probe

The aircraft –borne shrouded probe was tested for four different wind speeds for 10 μm AD particles. These speeds were 6.71, 17.88, 31.30, and 44.7 m/s (15, 40, 70, and 100 mph respectively) for a flow rate of 90 L/min through the shrouded probe. Also it was tested at 44.7 m/s (100 mph) with 30 L/min flow rate for 10 μm AD particles to check the behavior of the shrouded probe with the change in flow rate at 100 mph wind speed. These tests indicated that the transmission ratio of the shrouded probe is about 0.76 for 10 μm AD particles at 45 m/s (100 mph) wind speed for a sampling flow rate of 90 L/min. In order to optimize the performance of the shrouded probe it was decided to decrease the flow rate through the probe to 80 L/min and test it at the higher wind speed of 50.5 m/s (113 mph). The cruising speed of the aircraft on which this shrouded probe is mounted is about 55 m/s, however, due to the design limitation, this high speed cannot be achieved in our wind tunnel. The maximum speed on which the tests were run is 50.5 m/s (113 mph) with 10 μm AD particles and flow rate through the shrouded probe was maintained at 80 L/min.

Testing of the Manifold of Aircraft Sampling System Downstream of the Shrouded Probe

A manifold used in the aircraft, which is downstream of the shrouded probe, was also tested statically to check the penetration of thc 10 μm AD particles through the sampling system. The manifold was tested at flow rates of 30 L/min and 90 L/min.

QUALITY ASSURANCE

Uniformity of Particle Concentration and Flow Field

Different approaches were adopted for the tests to ensure that the presence of any non-uniformity of particle concentration and flow field (velocity profile) did not affect the results of the tests. The wind tunnel used for the tests has been checked for variation of particle concentration across the test plane. During tests with the shrouded probe in 0.86 m diameter test section, two isokinetic probes were run, along with the probe being tested. The average reading of these two isokinetic probes was used to eliminate any difference arising due to variation of particle concentration across the test plane. All tests in this study were run for durations long enough to ensure that the fluorometer readings for the filters plus wall wash solutions were always at least an order of magnitude greater than the background reading. Any data point used in this study is the statistical average of three to six replicate test results obtained for that operating condition.

Velocity and Flow Measurement

All instruments for measuring velocity and other flow parameters were calibrated prior to use. Leak checks were carried out on any system used. Velocity meters (VelociCal Model No. 8355 and Model No.1650, TSI, Inc., St Paul, MN) were used for measuring velocity. Rotameters (Dwyer Instruments, Michigan City, IN) and digital mass flow meters (Model 820, Top-Trak, Sierra Instruments, Monterey, CA) were used to measure the sampling probe flow rates. Rotameter readings were corrected for pressure drop to account for the difference in pressure levels in the test set-up and calibration. The following equation was used to obtain the actual flow rate:

$$Q_a = Q_o * \sqrt{1 - \Delta P / P_{atm}} \qquad [9]$$

Where Q_a = air flow rate at laboratory pressure,

Q_o = observed air flow rate in the rotameter,

ΔP = system pressure drop, and

P_{atm} = laboratory barometric pressure.

Calibrated Magnehlic vacuum gauges (Dwyer Instruments, Inc., Michigan City, IN) were used to determine the pressure drop of the system. Flow rate through the main sampling probe was determined by using a Roots meter (Model 5M 125 TC, Dresser Measurement, Houston, TX) where the flow rate was determined from noting the net gas volume and time required for that volume to flow through the meter.

Fluorometric Analysis

A fluorometer (model 450, Sequoia-Turner Corp., Mountain View, CA) was used to quantify the concentrations of sodium fluorescein collected by the test sampler and the isokinetic samplers. There are many factors that affect fluorometric analysis including intensity and wavelength of primary light, and transmission characteristic of excitation and emission filters used in the fluorometer. Stability of the fluorescent material can easily be disturbed by small changes in the environment, e.g., the pH, ionic state of molecule, nature of solvent, degree of subdivision of the material, viscosity, temperature, etc. (Kesavan, 2001). Kesavan et al. (2001) found that the optimum excitation and emission wavelengths for fluorescein are 492 nm and 516 nm respectively. Also that the fluorescence intensity from a fluorescein solution is pH dependent, but for values above 8, the intensity is both maximized and constant. The above requirements were fulfilled by use of the NB490 and SC515 filters and adding about 2% (v/v) of 1N NaOH to the solution to be analyzed.

RESULTS AND DISCUSSION

Effect of Wind Velocity on Transmission Ratio of Trigger Shrouded Probe

Figure 12 shows the effect of wind velocity on the transmission ratio of the 90 L/min trigger shrouded probe. The probe was designed to operate with near unity transmission ratio in the speed range of 4.47 m/s – 26.82 m/s (10 mph- 60 mph) with 13.41 m/s (30mph) as the nominal speed. From the graph it can be seen that for 10 μm AD particles, in the above mentioned speed range, the transmission ratio is between 0.88 and 1.28, with near unity transmission ratio at 30 mph. These tests were run with 5, 10, 15, and 17.5 μm AD particles. The size of 5 μm AD was considered to be near the lower limit of particles that exhibit inertial properties influencing the wall losses/deposition. Also 15 μm AD was considered as the upper limit of aerosol particles of interest in the bioaerosol studies. From the graph, it can be seen that the transmission ratio for all four particle sizes increases with an increase in velocity. For 10 μm AD particles the average transmission ratio increases from 0.85 to 1.28. For 5 μm AD particles the average transmission ratio increases from 0.89 to 1.1 and for 15 μm AD particles the average transmission ratio increases from 0.82 to 1.35.

It can be seen all particles exhibit approximately the same transmission ratio at 30 mph. The slope of the transmission ratio curve increases with an increase in particle sizes. It indicates the effect of sub-isokinetic sampling from the shroud into the inner sampling probe. To check the transmission ratio of the JPBDS trigger shrouded probe at low wind speeds, the tests were run at 0.5 m/s and 1 m/s with 10 μm AD particles. It can be seen that for these low velocities the transmission ratios are above 80% which shows the capability of a shrouded probe to sample at low speeds when the probe is directed into the flow.

Effect of Particle Size on the Transmission Ratio of the JPBDS Trigger Shrouded Probe

Figure 13 shows the effect of particle size on the transmission ratio of the trigger shrouded probe for constant velocity. Three different particle sizes 5, 10, and 15 μm AD were tested for the wind speed range of 4.47 m/s to 26.82 (10 mph to 60 mph, respectively) with increments of 4.47 m/s (10 mph). The graph shows that for a constant speed the transmission ratio decreases as the particle size increases for speeds up to 13.41 m/s (30 mph). For speeds higher than 13.41 m/s (30 mph) with an increase in particle size, the transmission ratio increases. This phenomenon can be explained as follows:

For low speeds, the sub-isokinetic effect of sampling from the shroud to the probe is low. This sub-isokinetic effect keeps increasing with an increase in wind speed. This is due to i) a constant speed flow through the probe and ii) increasing shroud velocity with an increase in the wind speed. The velocity reduction ratio for the aerosol entering from the free air to the shroud remains almost constant in this speed range. At the same time there are wall losses in the probe. These losses increase with the increase in particle size.

At lower wind speeds (up to 13.41), the sub-isokinetic effect is not very strong so the wall loss factor causes a decrease of transmission ratio with an increase in particle size. However, with the increase of wind speed above 13.41 m/s (30 mph), the effect of higher sub-isokinetic sampling from the shroud offsets the decrease of transmission ratio due to higher wall losses for increasing particle sizes.

Effect of Yaw Angle on the Transmission Ratio of the Trigger Shrouded Probe

Figure 14 shows the effect of yaw angle on the transmission ratio of the shrouded probe. These tests were performed for 10 μm AD particles and a wind speed of 2.25 m/s (5 mph). From the graph it can be seen that there is no appreciable change in the transmission ratio for yaw angles up to 45°. The transmission ratio for a 0° yaw angle at 2.25 m/s (5 mph) is about 84% and it is about 80% for yaw angles up to 45°. For a 90° yaw angle, the transmission ratio is about 50%. The reason for this behavior is the sampling from the core region of the shroud. While sampling at a yaw angle, the streamlines most affected are those in the outer region and they are not sampled. The inner core remains relatively undisturbed and that is the portion of the flow in the shroud that is sampled through the probe.

Penetration Curve for 90 L/min Demister

Figure 15 shows the penetration curve for the 90 L/min demister. It indicates that the cut-point diameter D_{50} (the aerodynamic diameter for which the inlet shows 50% collection efficiency) for this instrument is approximately 20 μm.

Effect of Wind Velocity on Transmission Ratio of 780 L/min Sampling Shrouded Probe

Figure 16 shows the effect of wind velocity on the transmission ratio of 780 L/min main sampling shrouded probe. The probe was designed to operate with near unity transmission ratio in the speed range of 4.47 m/s to 13.41 m/s (10 mph to 60 mph) with 13.41 m/s (30 mph) as the nominal speed. From the graph it can be seen that for 10 μm AD particles the transmission ratio is between 0.94 and 1.26, with near unity transmission ratio at 13.41 m/s (30 mph). These tests were run with 5, 10, 13, 15, and 17.5 μm AD particles. The size of 5 μm particles is considered to be approximately the lower limit of particles that exhibit inertial properties influencing the wall losses/deposition. The size of 15 μm AD is considered as the upper limit of aerosol particles of interest in the bioaerosol studies. From the graph, it can be seen that the transmission ratio for all five particle sizes increases with an increase in velocity. For 10 μm AD particles the average transmission ratio increases from 0.94 to 1.26. For 5 μm AD particles the average transmission ratio increases from 0.99 to 1.19. For 15 μm AD particles the average transmission ratio increases from 0.88 to 1.38.

Also it can be seen that all particles exhibit approximately the same transmission ratio at 4.47, 8.94, 13.41, and 17.88 m/s (10, 20, 30, and 40 mph, respectively). The slope of the transmission ratio curve increases with an increase in particle size. It indicates the effect of sub-isokinetic sampling from the shroud into the inner sampling probe. In order to check the transmission ratio of the main sampling shrouded probe at low wind speeds; the tests were run at 0.5 m/s and 1 m/s with 13 μm AD particles. The 13 μm AD particle size is the minimum cut point desired for the U.S. Navy application. It can be seen that for these low velocities the transmission ratio are above 80% which shows the capability of shrouded probe to sample at low speed when the probe is directed towards the direction of flow.

Effect of Particle Size on the Transmission Ratio of the 780 L/min Shrouded Probe

Figure 17 shows the effect of particle size on the transmission ratio of the main sampling shrouded probe for the JPBDS application. Three different particle sizes 5, 10, and 15 μm AD were tested for 4.47 m/s to 26.82 m/s (10 mph to 60 mph), with increments of 4.47 m/s (10 mph). The graph shows for a constant speed, the transmission ratio decreases as the particle size increases for speeds up to 8.94 m/s (20 mph). For speeds higher than 8.94 m/s (20 mph) with an increase in particle size, the transmission ratio increases. This phenomenon is similar to what was observed for the trigger shrouded probe and can be explained in a similar manner (see section entitled, " Effect of Particle Size on the Transmission Ratio of the Trigger Shrouded Probe").

Effect of Yaw Angle on the Transmission Ratio of the 780 L/min Sampling Shrouded Probe

Figure 18 shows the effect of yaw angle on the transmission ratio of the 780 L/min shrouded probe. This test was performed for 10 μm AD particles and a wind speed of approximately 2.25 m/s (5 mph). The transmission ratio for 0° yaw angle at this wind speed is about 0.97 and it is about 0.94 for yaw angles up to 45°. It indicates that at 5 mph the shrouded probe sampling ability is not affected appreciably due to a change in yaw angles up to 45°. While sampling at a yaw angle, the streamlines most affected are those in the outer region of the shroud and they are not sampled. The inner core remains almost undisturbed and sampled through the probe.

Effect of Wind Velocity on Transmission Ratio of Reference Shrouded Probe

Figure 19 shows the effect of wind velocity on the transmission ratio of a reference shrouded probe. The probe was designed to operate with near unity transmission ratio in the speed range of 6.71 m/s to 20.12 m/s (15 mph to 45 mph). Due to the application of the probe as a reference inlet in a wind tunnel for testing other inlets, the flow rate through the probe was changed according to the variable flow protocol of EPA Methods 5 and 17. The flow rate at 6.71 m/s (15 mph) was 16.7 L/min and at 20.12 m/s (45 mph) it was 50 L/min. From the graph it can be seen that for 10 μm AD particles the transmission ratio is between 0.99 and 1.06, which indicates negligible change in the transmission ratio between 6.71 m/s and 20.12 m/s (15 mph and 45 mph, respectively). These tests were run with 5, 10, and 15 μm AD particles. Again 5 μm is considered to be the approximate lower limit of particles that exhibit inertial properties influencing the wall losses/deposition and 15 μm AD is the upper limit of aerosol particles generally used for testing in the wind tunnel. From the graph, it can be seen that the transmission ratio for all three particle sizes increases with an increase in wind velocity. For 10 μm AD particles the average transmission ratio increases from 0.99 to 1.06. For 5 μm AD particles the average transmission ratio increases from 1.08 to 1.13 and for 15 μm AD particles the average transmission ratio increases from 0.89 to 1.06.

Also it can be seen all particles exhibit approximately the same transmission ratio at 30 mph. The slope of the transmission ratio curve increases with increase in particle sizes. It indicates the effect of sub-isokinetic sampling from the shroud into the inner sampling probe.

Effect of Particle Size on the Transmission Ratio of the Reference Shrouded Probe

Figure 20, shows the effect of particle size on the transmission ratio of the reference shrouded probe for three constant wind speeds. Three different particle sizes 5, 10 and 15 μm AD were tested for 6.71 m/s to 20.12 m/s (15 mph to 45 mph, respectively) in increments of 6.71 m/s (15 mph). The graph shows for a constant wind speed of 6.71 m/s (15 mph), the transmission ratio decreases as the particle size increases. For wind speeds of 13.41 m/s (30 mph) and 20.12 m/s (45 mph), the transmission ratio remains almost constant.

Effect of Wind Speed on the Transmission Ratio of Aircraft- borne Shrouded Probe

Figure 21 shows the effect of wind speed on the transmission ratio of the aircraft-borne shrouded probe. The probe was tested for 10 μm AD particles at four different wind speeds, 6.71, 17.88, 31, and 44.7 m/s (15, 40, 70, and 100 mph, respectively) for a flow rate of 90 L/min. From the graph it can be seen that the transmission ratio of the shrouded probe increases with an increase in wind speed. The transmission ratio was found to be 0.76 for a wind speed of 100 mph (45 m/s). The shrouded probe was also tested for 10 μm AD particles, 100 mph wind speed for a flow rate of 30 L/min through the probe. As expected the transmission ratio increased to 1.83. This is due to the higher sub-isokinetic sampling from the shroud to the inner probe. In order to improve the transmission ratio through the shrouded probe it was decided to decrease the flow rate through the probe from 90 L/min to 80 L/min and test it at speeds as close as possible to the design wind speed of the probe. This probe was originally designed for a cruising speed of 55 m/s. However, due to the limitations of the plenum chamber which was originally designed for 45 m/s, the probe was tested at 50 m/s (113 mph) with 10 μm AD particles at a sampling flow rate of 80 L/min. The transmission ratio for this condition was found to be 0.90. The two factors contributed to this increase of the transmission ratio: 1. An increase in transmission ratio with an increase in wind speed. 2. An increase in transmission ratio with the decrease of flow rate through the probe.

Transmission Ratio through the Aircraft-Borne Sampling System Manifold Downstream of the Shrouded Probe

The manifold downstream of the sampling system was tested statically for the transmission ratio for two different flow rates. These were 90 L/min and 30 L/min. the transmission ratio was found to be 0.79 for 90 L/min and 0.80 for 30 L/min. The non-unity transmission ratio through the manifold was due to two bends in the S-shape and use of different fittings in the system, e.g., a ball valve and flexible connector. During tests, the collection filter was installed at the manifold main outlet. The manifold also included four outlets at 90° to the flow direction in the manifold. These outlets were smaller in size compared to the main outlet of the manifold. The transmission ratio will be reduced if these outlets are used for sampling.

Transmission Ratio of the Complete Trigger System

In addition to the testing of the individual components of the complete trigger system, i.e., the shrouded probe, the demister, and the BAWS inlet, the complete trigger system was also tested for the transmission ratio. Figure 22 shows the transmission ratio of the complete trigger system at 13.21 m/s (30 mph) for 5, 10, and 15 μm AD particles using shrouded probe as sampling inlet. The transmission ratio decreases from 0.95 for 5 μm to 0.57 for 15 μm AD particles. Fig 23 shows the transmission ratio for the same system using shrouded probe as sampling inlet. The transmission ratio for 10 μm AD particles varies from 0.79 at 6.7 m/s (15 mph) to 1.19 at 26.82 m/s (60 mph).

Figure 24 shows the transmission ratio of the complete trigger system with BAWS inlet used for sampling. For 10 μm AD particles, the transmission ratio decreases from 0.40 at 3.6 m/s (8 mph) to 0.16 at 6.7 m/s (15 mph) wind speed. Figure 25 shows the transmission ratio of the complete system with BAWS inlet at 3.6 m/s (8 mph) wind speed for 5,10, 15, and 20 μm AD particles. The transmission ratio varies from 0.81 for 5 μm AD particles to 0.03 for 20 μm AD particles. Based on the results of these experiments, it was proposed to use the BAWS inlet for sampling up-to 4.47 m/s (10 mph) wind speed, due to low transmission ratio of this inlet at higher wind speeds. For wind speeds higher than 4.47 m/s (10 mph), the shrouded probe will be used as inlet, facing the direction of the wind.

SUMMARY AND CONCLUSION

Ambient sampling for particulate matter in air involves aspiration of sample from the air into an inlet device and subsequent transportation of the sample to the collector or analyzer. This process requires that the sample taken is representative of the air being sampled and also that the performance of the inlet is not affected by the factors such as wind velocity, turbulence intensity, direction of wind, etc.

Shrouded probes have been used for a long time for sampling in ducts and stacks of various chemical and nuclear installations. It has been found that the performance of the shrouded probes remains relatively unaffected by the change in factors mentioned above.

Three systems were designed and tested for ambient sampling using shrouded probes and commercial omni-directional inlets. Shrouded probes will be used for sampling at higher wind speeds (above 4.5 m/s) and omni-directional inlets for lower speeds. Two systems were required for Joint Point Biological Detection System (JPBDS) for the US Navy aircraft carrier ships. These systems operate at 780 L/min and 90 L/min. The wind speed can change from anywhere close to zero to up-to 26.82 m/s (60 mph). These systems were designed and tested for this speed range and for particle sizes in the range of 5 μm to 15 μm. The results indicated the ability of shrouded probes to perform within this wide range without appreciable change in the transmission ratio. For example, the trigger JPBDS system (90 L/min) has a transmission ratio of 0.78 at 6.71 m/s and 1.21 at 26.82 m/s for 10 μm AD particles. Similarly shrouded JPBDS main sampling probe (780 L/min) has a transmission ratio of 0.94 at 4.47 m/s and 1.23 at

26.82 m/s for 10 μm AD particles. The experiments also showed that changing yaw angles does not affect the transmission ratio of the shrouded probes appreciably. For example, for 10 μm AD particles, shrouded JPBDS trigger probe showed a transmission ratio of 0.84 to 0.79 for a change in yaw angles from zero to 45 degrees at a wind speed of 2.25 m/s. Similarly for 10 μm AD particles, shrouded JPBDS main sampling probe showed a transmission ratio of 0.97 to 0.94 for a change in yaw angles from zero to 45 degrees at a wind speed of 2.28 m/s. The complete trigger sampling system was also tested with the shrouded probe and the BAWS inlet and the demister. The results indicate the ability of shrouded probe to sample aerosols with a transmission ratio of more than 50% for 13 μm AD particles in a wind speed range of 4.47 m/s (10 mph) to 26.82 m/s (60 mph).

A system was also designed for medium speed application to be used as a reference sampler in a wind speed range of zero to 20.12 m/s (45 mph). It consists of Sierra-Andersen SA-246 inlet sampling continuously at 16.7 L/min for a speed range of zero to 6.71 m/s. For wind speeds between 6.71 m/s and 20.12 m/s, a shrouded probe was designed and tested. The flow rate through the shrouded probe will be changed according to the variable flow protocol of EPA Methods 5 and 17, from 16.7 L/min to 50 L/min for the above mentioned wind speed range. The results indicated that the transmission ratio of the shrouded probe remains close to unity for the wind speed range of 6.71 m/s to 20.12 m/s and for particles in the size range of 5 μm and 15 μm AD.

An aircraft-borne shrouded probe designed for high-speed application was also tested at wind speeds up-to 50 m/s for 10 μm AD particles. The shrouded probe performance was optimized by changing the flow rate through the probe. Inlet manifold, downstream of the shrouded probe was also tested for transmission ratio.

The wind tunnel was upgraded for testing the inlets at these higher speeds. Upgraded wind tunnel was tested for velocity and gas concentration profiles to check the compliance with ANSI/EPA standards.

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APPENDIX

FIGURES

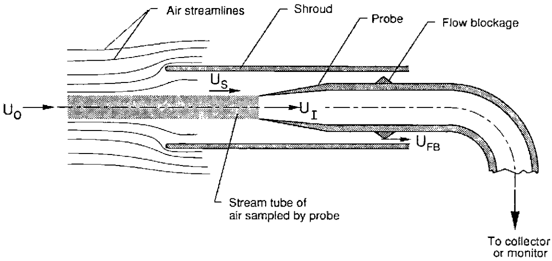


Figure 1. Principle of operation of shrouded probe.

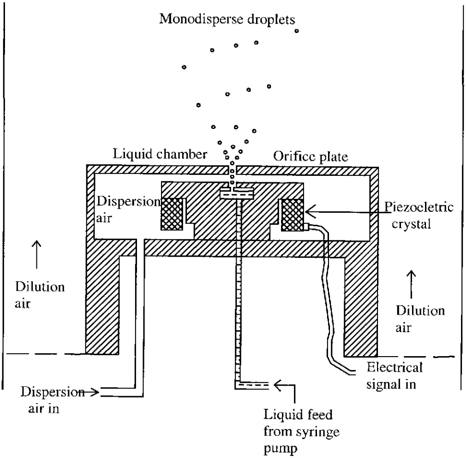
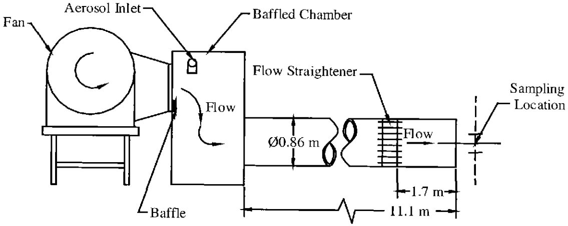
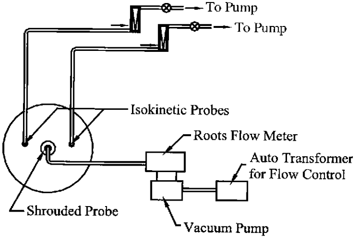


Figure 2. Schematic of vibrating orifice aerosol generator.

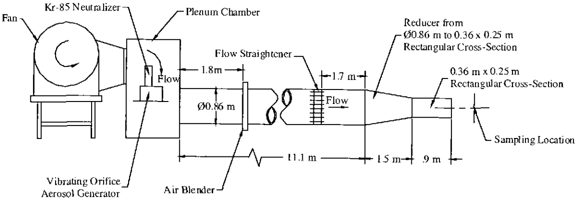


SIDE VIEW OF WIND TUNNEL

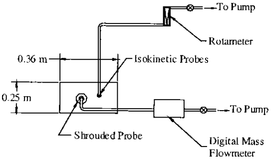


END VIEW OF WIND TUNNEL FACING INTO FLOW

Figure 3. Side and end views of wind tunnel used for testing with wind speeds up to 13.4 m/s (30mph).



SIDE VIEW OF WIND TUNNEL



END VIEW OF WIND TUNNEL FACING INTO FLOW

Figure 4. Side and end views of modified wind tunnel for speeds above 13.4 m/s (30 mph).

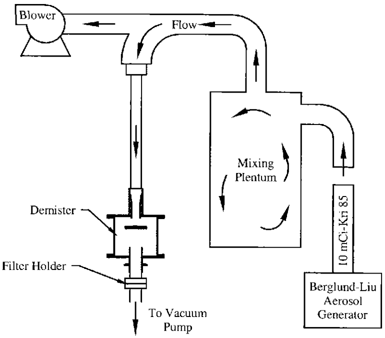


Figure 5. Schematic of duct.

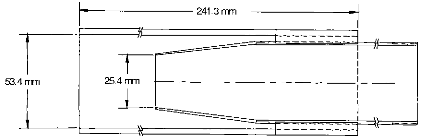


Figure 6. JPBDS trigger shrouded probe.

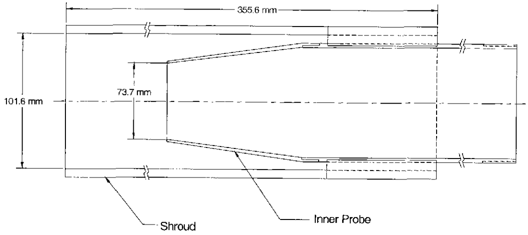


Figure 7. Shrouded JPBDS sampling probe.

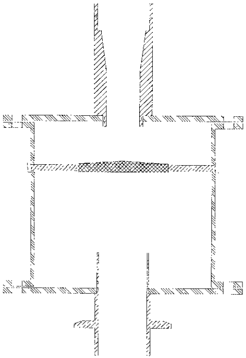


Figure 8. Demister assembly.

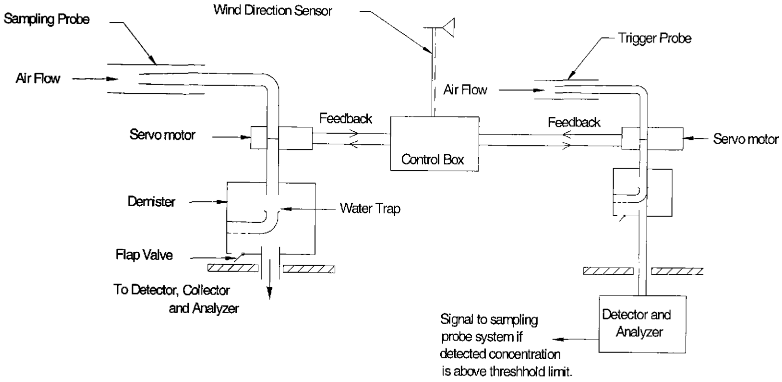


Figure 9. Schematic of complete sampling system for ship-borne application.

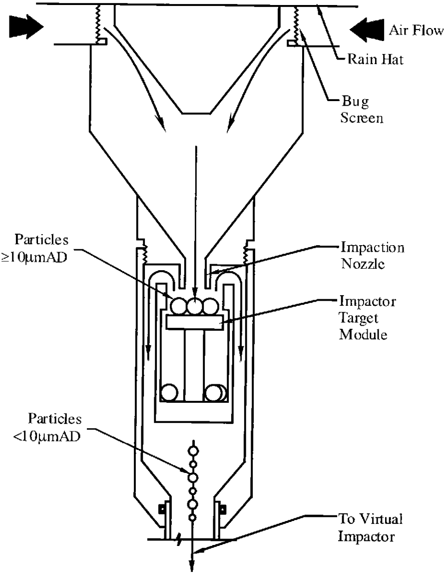


Figure 10. SA-246 inlet.

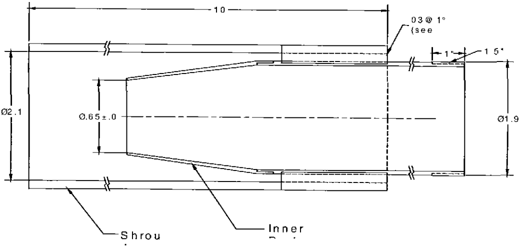


Figure 11. Reference shrouded probe.

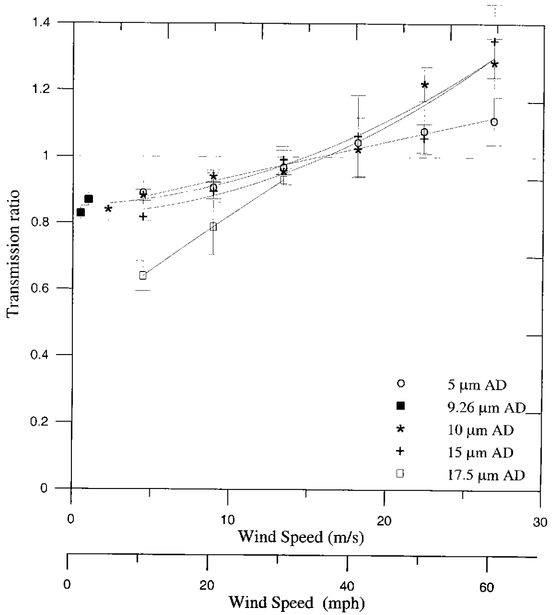


Figure 12. Transmission ratio as a function of wind speed for trigger shrouded probe (90 L/min).

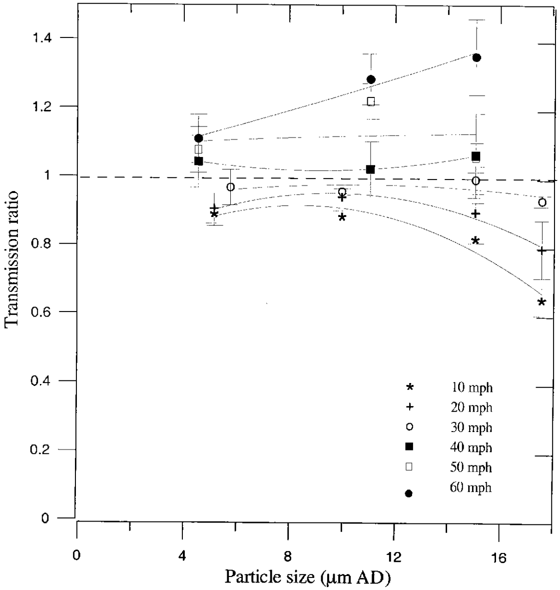


Figure 13. Transmission ratio as a function of particle size for trigger shrouded probe (90 L/min).

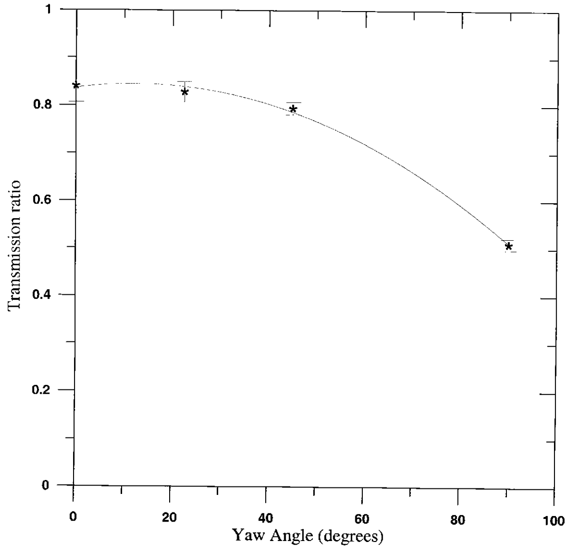


Figure 14. Transmission ratio as a function of yaw angle for trigger shrouded probe at 5 mph wind speed, 10 μm AD particles.

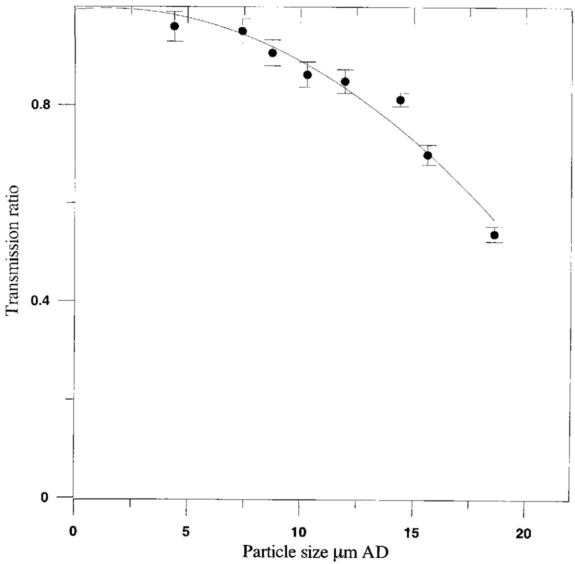


Figure 15. Transmission ratio as a function of particle size for 90 L/min demister.

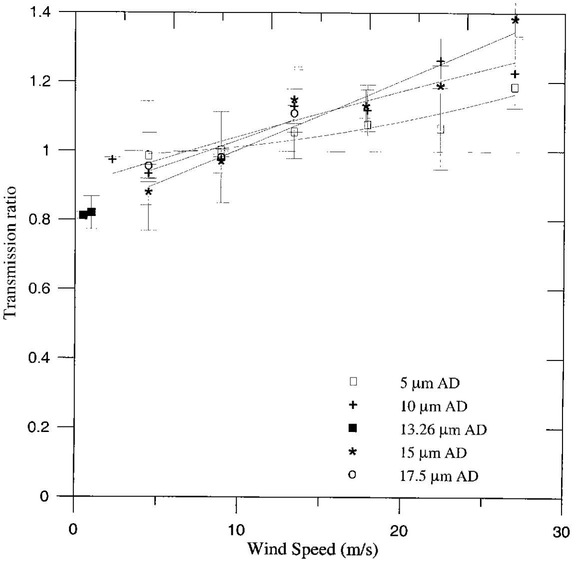


Figure 16. Transmission ratio as a function of wind speed for JPBDS sampling shrouded probe (780 L/min).

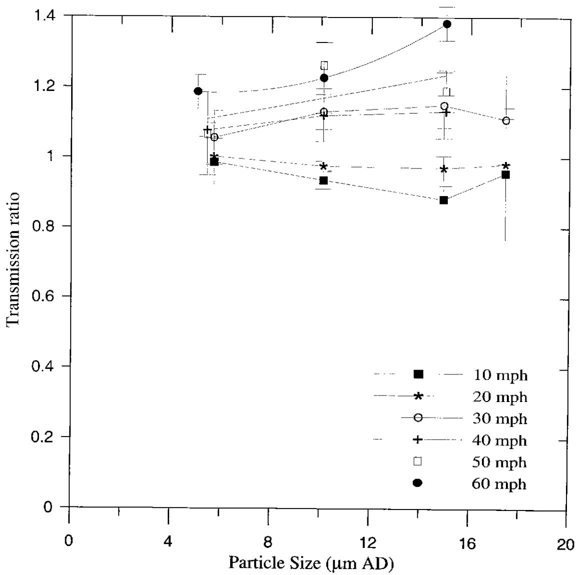


Figure 17. Transmission ratio as a function of particle size for main sampling shrouded probe (780 L/min).

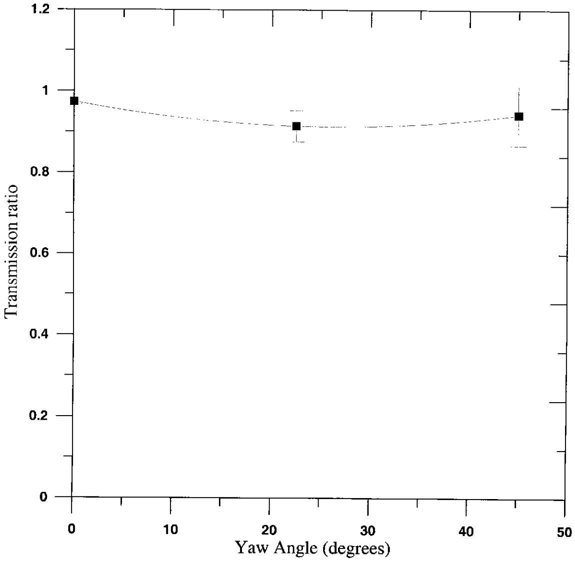


Figure 18. Transmission ratio as a function of yaw angle for JPBDS sampling shrouded probe (780 L/min).

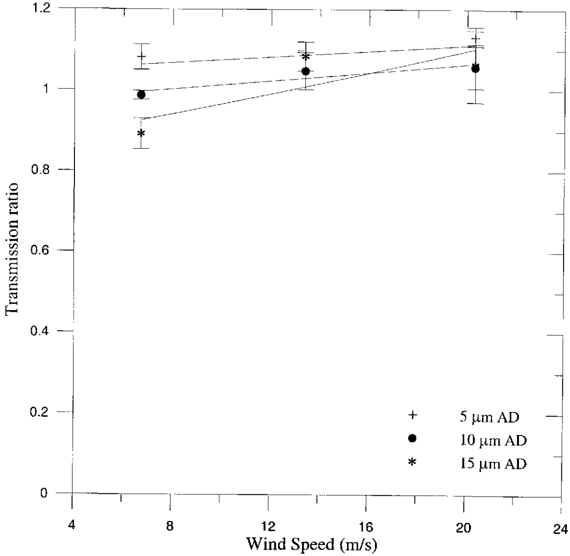


Figure 19. Transmission ratio as a function of wind speed for reference shrouded probe.

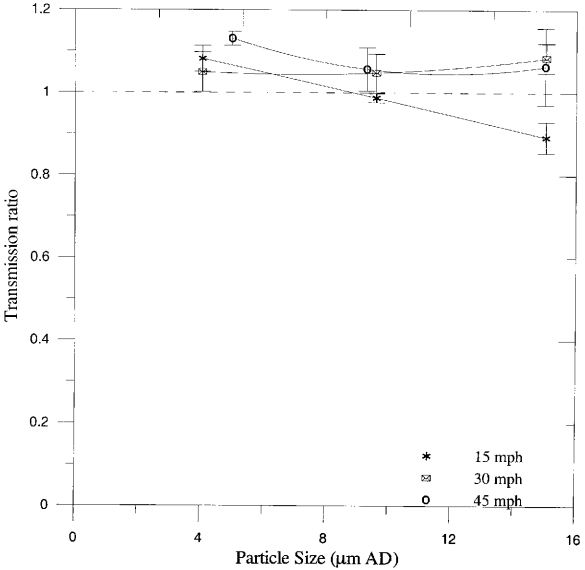


Figure 20. Transmission ratio as a function of particle size for reference shrouded probe.

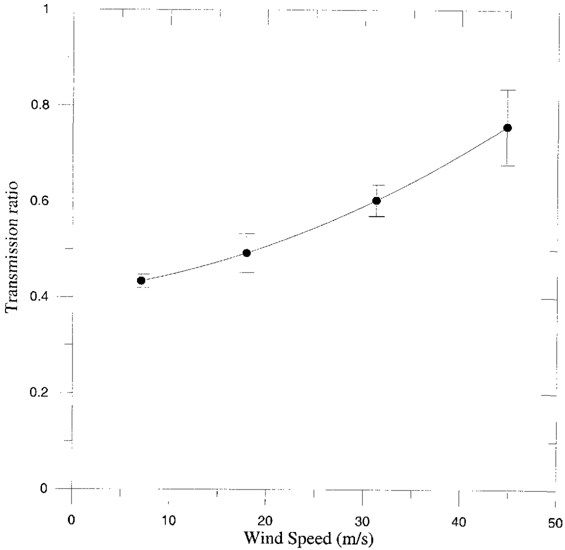


Figure 21. Transmission ratio as a function of wind speed for aircraft-borne shrouded probe.

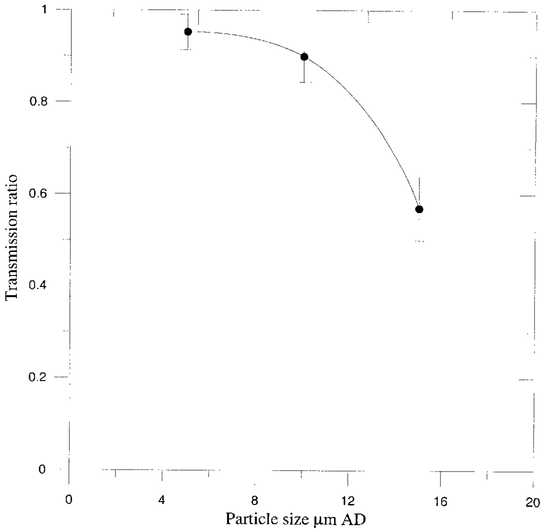


Figure 22. Transmission ratio as a function of particle size for shrouded trigger JPBDS system for 13.41 m/s wind speed.

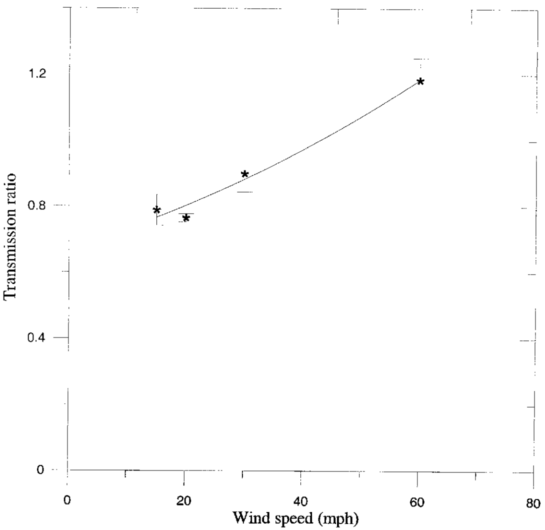


Figure 23. Transmission ratio as a function of wind speed for shrouded trigger JPBDS system for 10 μm AD particles.

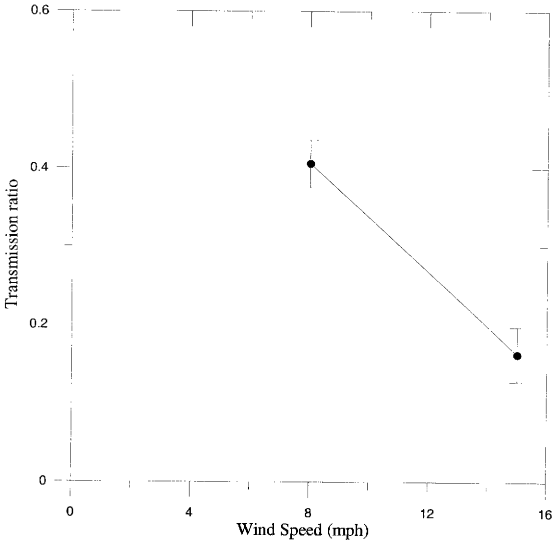


Figure 24. Transmission ratio as a function of wind speed for JPBDS system with BAWS inlet for 10 μm AD particles.

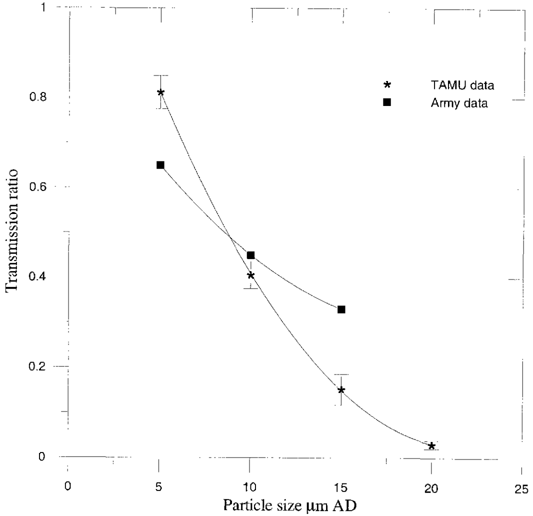


Figure 25. Transmission ratio as a function of particle size for JPBDS trigger system with BAWS inlet at 3.6 m/s (8 mph) wind speed.

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